COMPONENT MASSES OF THE YOUNG SPECTROSCOPIC BINARY UZ TAU E

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ABSTRACT

We report estimates of the masses of the component stars in the pre−main-sequence spectroscopic binary UZ Tau E. These results come from the combination of our measurements of the mass ratio, $M_2/M_1 = 0.28 \pm 0.01$, obtained using high resolution H-band spectroscopy, with the total mass of the system, (1.31±0.08)(D/140pc) $M_\odot$, derived from millimeter observations of the circumbinary disk (Simon et al. 2000). The masses of the primary and secondary are (1.016±0.065)(D/140pc) $M_\odot$ and (0.294±0.027)(D/140pc) $M_\odot$, respectively. Using the orbital parameters determined from our six epochs of observation, we find that the inclination of the binary orbit, 59.8±4.4 degrees, is consistent with that determined for the circumbinary disk from the millimeter observations, indicating that the disk and binary orbits are probably coplanar.

Subject headings: binaries: spectroscopic — stars: pre−main-sequence

1. Introduction

This letter reports on the most recent progress in our efforts to convert pre−main-sequence (PMS) single-lined spectroscopic binaries (SB1s) to double-lined systems (SB2s) in order to (1) provide dynamical mass data for the calibration of young star evolutionary models, and (2) to help determine the unbiased, low-mass PMS mass ratio distribution of SB2s (Prato et al. 2002). Dynamical mass ratios have almost exclusively been measured in visible light and show a distribution weighted strongly towards unity. Because this is probably a selection effect, given that the detection of a spectroscopic secondary is far easier for flux, and therefore mass, ratios close to unity (Mazeh et al. 2002), the underlying astrophysical distribution of the mass ratio values is unknown. In Prato et al. (2002) we applied infrared

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(IR) spectroscopy to the problem of identifying the secondary stars in PMS SB1s because these low-mass companions are red and thus are more readily detectable in IR light. This project is an endeavor to convert all known, PMS SB1s to SB2s. Prato et al. (2002) show that this approach yields the smallest mass-ratios ever derived for PMS SB systems. To date, all of the IR-converted SB2s display values of $q = M_2/M_1 < 0.6$ (Steffen et al. 2001; Prato et al. 2002).

We have applied this IR approach to UZ Tau E, identified as a 19.1 day period SB1 by Mathieu et al. (1996). It forms a hierarchical quadruple with UZ Tau W, itself a $0''.34$ binary, $\sim 4''$ to the west (Simon et al. 1995). Together with GW Ori, DQ Tau (Mathieu et al. 1991, 1997), and V4046 Sgr (Quast et al. 2000), UZ Tau E is one of only 4 classical T Tauri star SBs known. Emission line and color diagnostics indicate that accretion is occurring on to the stars in UZ Tau E (Kenyon & Hartmann 1995) despite the expected formation of a gap in its circumbinary disk (Artymowicz & Lubow 1994). The presence of the circumbinary disk around the UZ Tau E SB enabled Simon et al. (2000) to measure the distance dependent, total binary mass by mapping the Keplerian rotation of the ^{12}CO gas in the disk. Thus, with the determination of the mass ratio, we are able to calculate the component stellar masses and orbital inclination. In §2 we briefly describe our observations and data reduction. The analysis and results appear in §3. Section 4 provides a brief discussion.

2. Observations and Data Reduction

H-band observations were made with the Keck II near-IR spectrometer, NIRSPEC, a cross-dispersed, cryogenic echelle spectrometer employing a 1024×1024 ALADDIN InSb array detector (McLean et al. 1998, 2000). The resolving power was $R = 24,000$ and $R = 30,000$ for the non-adaptive optics (non-AO) and AO modes, respectively. For AO mode observations, dispersion solutions were derived using arc lamp lines. Otherwise we used night sky OH lines (Rousselot et al. 2000). Integration times for a single exposure were usually 300 s. Further details about the observations are provided in Prato et al. (2002).

The data were reduced using REDSPEC, software designed at UCLA for the analysis of NIRSPEC data[4]. For the analysis described here we used only order 49. The central wavelength of this order is $\sim$1.55 μm; order 49 is almost completely free from terrestrial absorption lines. Table 1 provides a log of the observations; column (1) gives the UT date, column (2) the observing mode (i.e. non-AO or AO), and column (3) the modified Julian day of the observation.

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[4]See: http://www2.keck.hawaii.edu/inst/nirspec/redspec/index.html

3. Analysis and Results

Figure 1 shows the spectra from the six epochs of observations. These were analyzed as described in Mazeh et al. (2002) and Prato et al. (2002) using the two-dimensional cross-correlation program TODCOR (Zucker & Mazeh 1994) and our library of stellar templates. For every epoch of observation, the secondary star spectrum was detected; velocities for the primary and secondary stars appear in columns (4) and (5) of Table 1. Uncertainties in the velocities reflect the addition in quadrature of the internal uncertainty in the TODCOR analysis and the ± 1 km s^{-1} uncertainty between our velocity reference frame, as estimated from the template star radial velocities, and that of others (Prato et al. 2002).

The stellar templates that produced the maximum correlation in the TODCOR analysis were either GL 763 or GL 752A for the primary, and GL 213 or GL 402, rotationally broadened to 25$-$30 km s^{-1}, for the secondary. The Centre de Données astronomiques de Strasbourg (SIMBAD) lists GL 763 and GL 752A with spectral types of M0 and M3, respectively, however, GL 752A is probably misclassified. Figure 1 of Prato et al. (2002) shows the spectra in our template library; at 1.55 μm, the spectrum of GL 752A appears to be earlier than M3 and is better matched to an M0 or M1.5 star. We therefore regard the best fitting primary templates as consistent with the M1 visible light spectral classification given by Kenyon & Hartmann (1995) for the entire UZ Tau E system. The spectral types of the best fitting secondary templates are both M4.

The average 1.55 μm flux ratio is $H_2/H_1 = 0.47$. As discussed in Prato et al. (2002), the cross-correlation analysis yields component velocities that are very reliable because they are based on many spectral lines. However, estimates of spectral type and flux ratio must be regarded as only representative because of the mismatch in surface gravity and metallicity between the main-sequence star templates and the PMS targets.

The SB1 results reported by Mathieu et al. (1996) give the orbital period, $P = 19.1$ days, the eccentricity, $e = 0.28$, the projected primary semi-major axis, $a_1 sini = 0.03$ AU, and the primary semi-amplitude, $K_1 = 17$ km s^{-1}. We derived the orbital elements of the UZ Tau E SB2 by a least-squares minimization. The phases which appear in column (6) of Table 1 were calculated using our value for the period derived from this procedure, $P = 19.048 \pm 0.011$ days. Figure 2 shows the orbital fit to the observed velocities and Table 2 lists our orbital elements in standard notation following Heintz (1978). We derive a mass ratio of $q = M_2/M_1 = 0.289 \pm 0.025$. Our results are in excellent agreement with the parameters in common measured by Mathieu et al. (1996).

By measuring the Keplerian rotation of the UZ Tau E circumbinary disk, Simon et al. (2000) determined $M_{total} = (1.31 \pm 0.08)(D/140pc)M_\odot$ for the binary. This scales with distance because it depends on the radial scale of the disk. Combining M_{total} with q, derived here, we obtain the orbital inclination $(sini = 0.864 \pm 0.039)(140/\mathrm{D\ pc})^{1/3}$, or $i = 59.8{\pm}4.4$ degrees for $D = 140$ pc (Kenyon et al. 1994), and the component masses, $M_1 = 1.016 \pm 0.065 M_\odot$ and $M_2 = 0.294 \pm 0.027 M_\odot$.

4. Discussion

The inclination of the UZ Tau E circumbinary disk measured by its ^{12}CO J=2−1 rotation is, for $D = 140$ pc, 56 ±2 degrees; the apparent projected inclination of the disk in 1.3 mm continuum emission is 54 ±3 degrees (Simon et al. 2000). This is consistent, within the uncertainties, with our derived value, $i = 59.8{\pm}4.4$ degrees ($D = 140$ pc), for the orbit of the spectroscopic binary. The range of values is $i = 56 - 65$ degrees for $D = 160 - 120$ pc. This consistency between the orbital and circumbinary disk inclinations indicates that the stellar orbit and the disk are probably coplanar.

Figure 3 shows the components of UZ Tau E plotted on the H-R diagram. The M1 primary and M4 secondary were assigned effective temperatures of 3700±150 K and 3300±150 K, respectively, from the conversion presented in Figure 5 of Luhman (2000). Using $H_{total} = 8.46$ mag for the SB2, corrected for $A_V = 1.49$ mag (Kenyon & Hartmann 1995) and apportioned according to the flux ratio, $H_2/H_1 = 0.47$ (§3), we obtained the component H-band magnitudes. Applying the appropriate bolometric correction, 2.31 mag for the M1 and 2.44 mag for the M4 (Hartigan et al. 1994; Tokunaga 2000), then enabled the calculation of the component luminosities, $L_1 = 0.63^{+0.19}_{-0.17}\ L_\odot$ and $L_2 = 0.28^{+0.09}_{-0.07}\ L_\odot$. The large uncertainties in L_1 and L_2 are domianted by the ±20 pc uncertainty in the location of UZ Tau E along the line of sight to the Taurus SFR. The luminosity ratio, $L_2/L_1 = 0.44 \pm 0.18$, is approximately equal to the H-band flux ratio (Prato et al. 2002).

The PMS evolutionary tracks of Baraffe et al. (1998) and Palla & Stahler (1999) are shown in Figure 3. Both sets of tracks indicate that the system is relatively young, $\sim 1 \times 10^6$ years. For both sets of tracks, the secondary star lies within 1 σ of the mass track appropriate to its derived dynamical mass; however, the primary star appears on mass tracks with a value 3−4 σ smaller than its dynamically derived mass. The model-based mass ratios, $q = 0.52 \pm 0.23$ for the tracks of Baraffe et al. (1998) and $q = 0.38 \pm 0.23$ for those of Palla & Stahler (1999), are consistent with the dynamical mass ratio, $q = 0.29 \pm 0.03$ to within 1 σ, but this is a result of the propagation of the uncertainties in the track-derived masses, which are as high as ∼50 %.

It is unlikely that the source of this discrepancy lies in the simple application of the H-

band flux ratio to apportion the component luminosities, even though this ratio is uncertain (§3), because the mass of an M1 star is relatively insensitive to luminosity on the tracks of both Baraffe et al. (1998) and Palla & Stahler (1999). We can rule out contamination by a third component in the UZ Tau E system on the basis of our cross-correlation analysis as well as mm-wave and near-IR imaging of the system (e.g., Dutrey et al. 1996).

Several origins for this discrepancy are possible. (1) UZ Tau E may be on the near side of the Taurus star forming region at a distance of ∼120 pc. The total mass of the SB2 system as derived by Simon et al. (2000) is a function of distance. (2) The mass of the spectroscopic system measured by Simon et al. (2000) may be an overestimate if a dense ring of circumbinary material with a radius of a few AU is present in the disk. (3) The rotation of the circumbinary disk may be non-Keplerian. (4) The main-sequence templates may be poorly matched to the PMS objects and hence yield incorrect spectral types. (5) Given the complexities of the calculations of PMS evolution at very young ages, some uncertainties may also be expected in the theoretical tracks.

To test the plausibility of the first two possibilities listed above we combine a 20 pc (14 %) underestimate in the distance to UZ Tau E and a 5 % overestimate in the total stellar mass measured at millimeter wavelengths, resulting from the presence of an undetected dense ring of material within the UZ Tau E circumbinary disk, similar to the structure in the circumbinary disk of GG Tau (Guilloteau et al. 1999). We now derive $M_{total} = 1.07 \pm 0.07$ $M_\odot$, yielding $M_1 = 0.83 \pm 0.05$ $M_\odot$ and $M_2 = 0.24 \pm 0.02$ $M_\odot$. The revised dynamical value of M_1 still departs by $2-3$ σ from the location of the star on the H-R diagram. The difference in the dynamical and model values for M_2 is still <1 σ.

The low-surface gravity expected in a young, PMS star may cause its spectrum to appear to be later than the object's mass would indicate (White et al. 1999; Luhman 2000). However, precisely to account for such an effect, we have used the spectral type to effective temperature conversion of the Luhman (2000) to place the SB2 components on the H-R diagram. In addition, agreement between the tracks and the dynamically measured secondary star mass is inconsistent with this interpretation. On the Baraffe tracks, the UZ Tau E secondary appears to be slightly *more* massive than expected from the dynamical data. On the tracks of Palla & Stahler, it is slightly less massive than expected, but for both sets of tracks, the discrepancy in the position of the secondary is <1 σ (Figure 3). To investigate this phenomenon further, observations and analyses of the type we report here are required to connect stars of well-determined mass with the appropriate spectral types and effective temperatures.

DQ Tau is also a short period (16 day) classical T Tauri SB2 (Mathieu et al. 1997). It is remarkable in that accretion onto the central stars from a circumbinary disk is regulated by the eccentric orbit of the stars. Most photometric studies of UZ Tau E have not isolated the system from UZ Tau W; it is unclear if photometric variability synchronized with the period of the SB2 is present. If the discrepancy between our dynamical mass measurement and the masses obtained from the H-R diagram is attributable to unusual accretion processes, it is difficult to understand how such would cause a star to appear *less* massive, i.e. appear to have a later spectral type, than the dynamical measurement implies.

Quast et al. (2000) studied the components in another classical T Tauri SB2, V4046 Sgr, a 2.4 d period system, and found a discrepancy between the mass ratio determined dynamically, $q = 0.94$, and from an evolutionary model, $q = 0.80$. However, deriving uncertainties for their observed and theoretical mass ratio, from their Table 1 and Figure 3, respectively, we find that their numbers are consistent to within 1 σ and therefore are not discrepant. The total mass of the V4046 Sgr SB2 has not been measured dynamically so the individual stellar masses are not known.

Quast et al. (2000) suggest that the unusual behavior in V4046 Sgr might be attributable to the distorted structure of stars in such a short period binary. However, in UZ Tau E, with an orbital period of $\sim$19 d, the tidal effects will be much smaller. With an orbital semimajor axis of $\sim$33 $R_\odot$, there is only a weak interaction between the 2$-$3 $R_\odot$ radius components. Unfortunately, it is not possible at the present time to deconvolve the effects of metallicity, rotation, and surface gravity simultaneously for blended components of an SB2. A combination of some of the factors discussed above may ultimately be responsible for the inconsistencies discussed in this letter. Clarification of the questions raised here may require very high spatial resolution orbital mapping with future facilities such as the *Space Interferometry Mission*.

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Table 1. Summary of Observations and Analysis

UT Date of Observation	Mode of Observations	Modified Julian Day (2,450,000+)	$v_{primary}$ (km s^{-1})	$v_{secondary}$ (km s^{-1})	Phase
2000 Nov 11	non-AO	1859.6	5.8$\pm$1.04	44.2$\pm$1.49	0.776
2001 Jan 5	AO	1914.2	15.0$\pm$1.12	11.7$\pm$1.64	0.643
2001 Aug 4	non-AO	2125.6	8.5$\pm$1.04	39.8$\pm$1.49	0.745
2001 Aug 31	AO	2152.6	21.8$\pm$1.04	-11.0$\pm$1.72	0.163
2001 Oct 10	non-AO	2192.6	27.2$\pm$1.08	-23.7$\pm$2.33	0.264
2002 Feb 6	non-AO	2311.2	27.4$\pm$1.12	-31.5$\pm$1.89	0.492

Table 2. Orbital Elements and Derived Properties of UZ Tau E

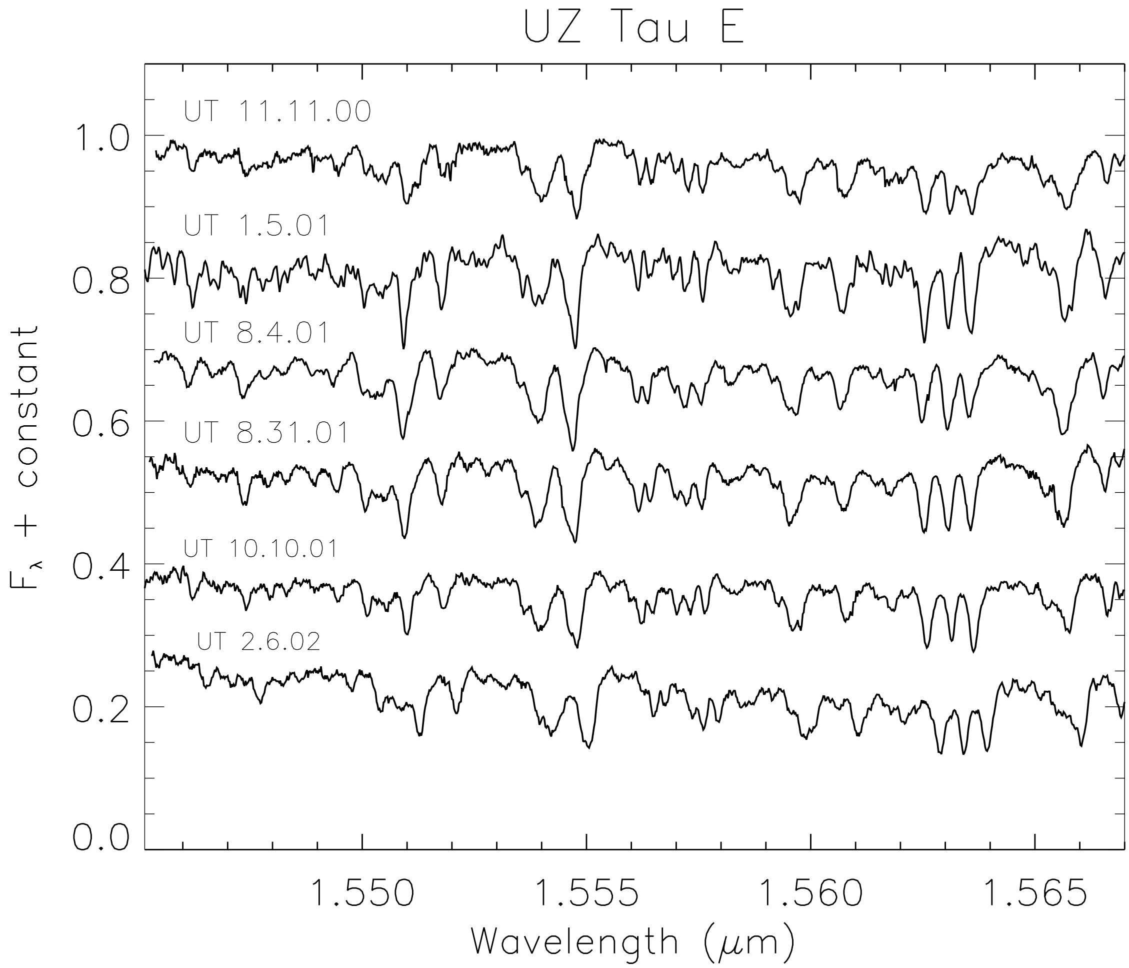
$P = 19.048 \pm 0.011$ days
$\gamma = 14.8 \pm 0.6$ km s^{-1}
$K_1 = 17.4 \pm 1.4$ km s^{-1}
$K_2 = 60.2 \pm 3.0$ km s^{-1}
$e = 0.237 \pm 0.030$
$\omega = 220.5 \pm 7.6$ degrees
$T = 2,452,092.45 \pm 0.44$ MJD
$M_1 sin^3 i = 0.655 \pm 0.098 M_\odot$
$M_2 sin^3 i = 0.190 \pm 0.031 M_\odot$
$q = M_2/M_1 = 0.289 \pm 0.025$
$a_1 sini = (4.42 \pm 0.35) \times 10^6$ km
$a_2 sini = (15.31 \pm 0.71) \times 10^6$ km
$M^{a}_{total} = 1.31 \pm 0.08 M_\odot$ for D=140 pc
$M_1 = 1.016 \pm 0.065 M_\odot$ for D=140 pc
$M_2 = 0.294 \pm 0.027 M_\odot$ for D=140 pc
$i = 59.8 \pm 4.4$ degrees for D=140 pc

[a]Data from Simon et al. (2000)

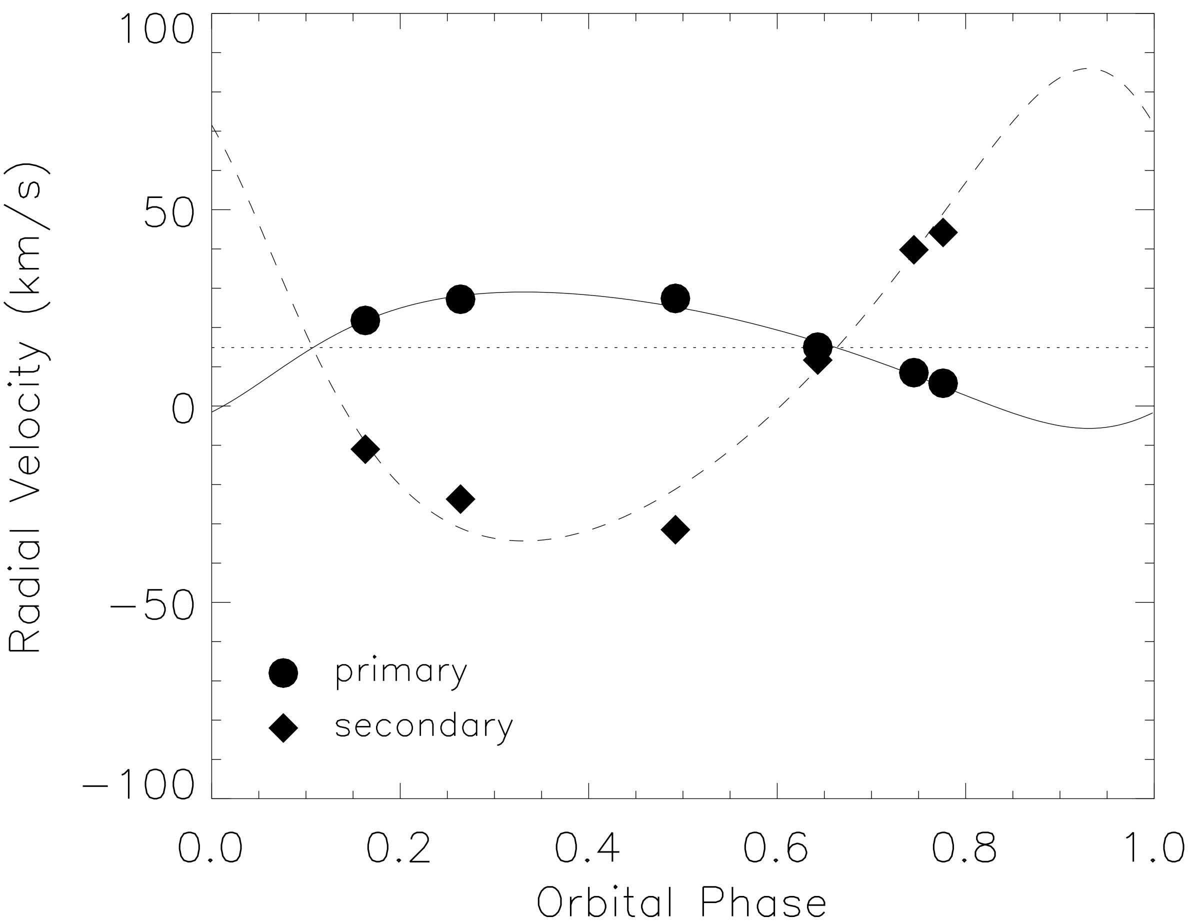
Fig. 1.— Six epochs of order 49 NIRSPEC spectra of the UZ Tau E spectroscopic binary. No heliocentric or radial velocity corrections have been applied. The spectral continuum has been flattened.

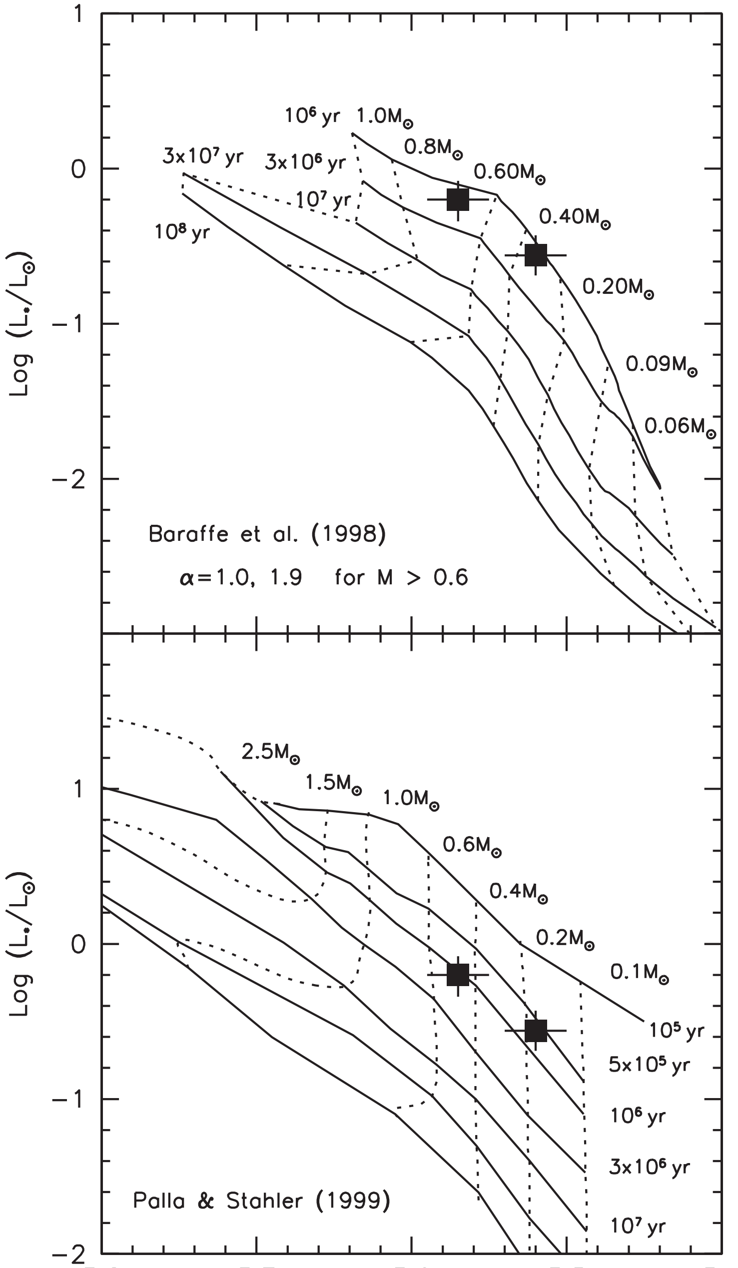
Fig. 2.— Radial velocity as a function of phase for UZ Tau E. The circles represent primary star data and the diamonds secondary star data. The best fit to the data is shown as a solid line for the primary star and a dashed line for the secondary. A dotted, horizontal line indicates the center of mass velocity of the system. The uncertainties in the velocities (Table 1) are smaller than the plotting symbols.

Fig. 3.— The H-R diagram showing the components of the UZ Tau E system on the tracks of Baraffe et al. (1998) and Palla & Stahler (1999). The spectral type to temperature conversion for the component M1 and M4 stars was made using the scale defined by Luhman (2000). Uncertainties in T_{eff} correspond to one spectral subclass. The derivation of the luminosities is described in the text. In the upper panel, the mixing length parameter, α, is 1.0 for $M < 0.6 M_{\odot}$ and 1.9 for $M > 0.6 M_{\odot}$.



UZ Tau E
UT 11.11.00
UT 1.5.01
UT 8.4.01
UT 8.31.01
UT 10.10.01
UT 2.6.02
1.0
0.8
0.6
0.4
0.2
0.0
F_λ + constant
1.550
1.555
1.560
1.565
Wavelength (μm)


100
50
0
−50
−100
Radial Velocity (km/s)
0.0
0.2
0.4
0.6
0.8
1.0
Orbital Phase
primary
secondary


Baraffe et al. (1998)
α=1.0, 1.9 for M > 0.6
10⁶ yr
1.0M⊙
0.8M⊙
3x10⁷ yr
3x10⁶ yr
10⁷ yr
10⁸ yr
0.60M⊙
0.40M⊙
0.20M⊙
0.09M⊙
0.06M⊙
Log (L*/L⊙)
Palla & Stahler (1999)
2.5M⊙
1.5M⊙
1.0M⊙
0.6M⊙
0.4M⊙
0.2M⊙
0.1M⊙
10⁵ yr
5x10⁵ yr
10⁶ yr
3x10⁶ yr
10⁷ yr
Log (Teff)